Chapter I Introduction

I-1: Hydro-geomorphic processes in humid forested mountains

To understand landform evolution in humid forested mountains requires discussion on geomorphic processes in valley heads. Many studies focused on the role of shallow landsliding on landform evolution in humid forested mountains. Tsukamoto *et al*. (1973, 1982) suggested that most of the shallow landslides induced by intensive rainfall occur on the convergent slopes where valleys tend to expand upstream. They named such convergent slopes zero-order basins. Dietrich and Dunne (1978) analyzed sediment budget in a hollow and suggested that there is a repetition of the sediment discharge caused by debris flows and the sediment supply caused by diffusive processes such as soil creep.

Studies on the dating and recurrence intervals of shallow landslides (Reneau *et al*., 1986; Shimokawa *et al*., 1989; Yoshinaga and Saijo, 1989) reported that shallow landslides have recurrence intervals at the same slope ranging from several hundreds to several thousands years. The occurrence ratio of shallow landslides to unit area was influenced by bedrock lithologies (Hayashi, 1985; Onda, 1989, 1992). In the mountains where shallow landslides rarely occur, it is unknown whether or not the shallow landslides contribute to landform evolution.

From 1980's to 1990's, many studies discussed the interactions between landform evolution and hydrological processes with hydro-geomorphic observations. One of the primary issues of hydrogeomorphology is to clarify the difference in runoff processes in small watersheds with various lithologies (Onda, 1989, 1992, 1994a; Ebizuka and Kondoh, 1990; Hirose *et al*., 1994; Komatsu and Onda, 1996; Tanaka *et al*., 2002). These studies were devoted to hydrological observations, and reported the difference in rainfall-runoff responses in headwater basins with various lithologies. Furthermore, Onda (1989, 1992, 1994a) discussed how the differences in rainfall-runoff responses affect the contrast between erosion processes and landform. For example, Onda (1989, 1992) suggested that a granitic basin with shallow regolith (< 1 – 2 m) favors subsurface storm flow, which facilitates shallow landslides. On the other hand, a granodiorite basin with deep regolith (> 5 m) facilitates unsaturated percolation and resulting seepage erosion.

There are many observations of both runoff and sediment discharge in headwater basins. In humid areas, simultaneous observations were conducted in the areas where rills or gullies developed, such as devastated hills (Uchida *et al*., 2000; Kimoto *et al*., 2002) or volcanic areas immediately after eruptions (Yamakoshi and Suwa, 1998). However, few studies observed simultaneously runoff and sediment discharge from headwater basins in humid forested mountains. Sidle (1988), Sonoda (1993), and Gomi and Sidle (2003) observed bedload yield from headwater basins, and revealed that the bedload yield is empirically expressed as a power function of peak or averaged stream discharge. Onda (1994b) observed seepage erosion from springs at the foot of slopes, and suggested a qualitative model for head-slope retreat by seepage erosion. Sediment discharge from a spring was also observed to analyze the effect of subsurface hydraulic gradient on seepage erosion (Terajima *et al*., 1997, 2001). Hirose (1996) measured suspended load, dissolved load, and bedload in four small headwater basins with different lithologies, and estimated denudation rate in each basin.

These many studies on hydro-geomorphic processes, however, had no quantitative discussion about landform evolution. For example, although Onda

(1992, 1994a) qualitatively discussed the feedback effect of runoff processes on landform evolution through observations in basins with different lithologies, these studies did not propose a quantitative model. Most of the studies on bedload transport discussed dynamic process of sediment transport itself, but poorly discussed landform evolution. Although Hirose (1996) revealed the quantitative difference in denudation rate in various bedrocks, he did not discuss landform evolution. One of the primary issues in the hydrogeomorphology, which focuses on an interaction between hydrological processes and landform evolution (Okunishi, 1991, 1994), is to explain the effect of runoff processes on landform evolution through quantitative models.

I-2: Channel initiation models

Dietrich and Dunne (1993) defined a channel head as '*the upstream boundary of concentrated water flow and sediment transport between definable banks*'. Exploring hydro-geomorphic processes in channel heads is quite important to discuss landform evolution in valley heads. Dietrich and Dunne (1993) pointed out three geomorphological issues on channel heads: (1) *where the channel head locates within the valley network*, (2) *how this position may change with external influences and internal adjustments*, and (3) *what role fluctuations in channel-head position play in valley development and persistence*.

Although the second and third issues were not quantitatively studied, the first issue, i.e. the controlling factors affecting location of channel heads, was traditionally discussed. Horton (1945) firstly argued the controlling factors for the channel-head location on the well-known concept of 'belt of no erosion'. He suggested that rill initiation occurs when the shear stress of overland flow exceeds a critical shear stress at the ground surface, in other words, when the depth of overland flow exceeds a critical depth. Since the depth of overland flow on a slope increases with increasing distance from the divide, the location of rill heads is controlled by the distance from divide (Horton, 1945). Although the Horton's concept can be applied to arid or semi-arid zones where the Hortonian overland flow predominates, his concept cannot be directly applied to the humid forested mountains where subsurface or groundwater flow predominates (Kirkby and Chorley, 1967; Tanaka, 1982).

Smith and Bretherton (1972) mathematically explained channelizing condition through combining equations of continuity with a sediment transport law. They suggested that channelizing occurs when $q_s < q(\partial q_s/\partial q)$ occurs (where, q_s is sediment flux per unit width, q is water flux per unit width). Kirkby (1980) suggested a model for landform evolution including slope and gully development, which is based on the Smith and Bretherton's threshold combining with the sediment transport law for surface wash process. Moreover, Kirkby (1986, 1987) simulated landform evolution based on the thresholds for surface wash and shallow landslide. He argued that relation between hollow gradient and source area depends on the occurrence of subsurface flow, and that source area decreases with increasing hollow gradient in the case of shallow landslide. Although many notable findings were obtained from these studies, relations between these models and field data were not discussed.

Montgomery and Dietrich (1988, 1989) explained the threshold for channel initiation based on field measurements as well as physical theories. They measured source area and local slope at channel heads in Tennessee Valley, Marin County, California. Here, the term 'local slope' means gradient immediately above a channel head along the hollow axis. They reported an inverse relationship between source area and local slope at channel heads. The area-slope conditions required for shallow landsliding can be explained with a coupled function of saturated throughflow predicted by topographic convergence (Iida, 1984) and an analytical equation for infinite slope instability. They suggested that the observed area-slope data at channel heads are consistent with the function, into which hydraulic conductivity and shear strength of slope material, regolith depth, and a suitable rainfall condition were substituted.

Dietrich *et al*. (1992, 1993) theoretically analyzed threshold for the channel initiation caused by saturation overland flow, and suggested a channel initiation model with the form of $a > \alpha S^{\beta} + cS$ (where a is area draining into unit contour length, S is local slope immediately above channel heads, and α, β and c are constants). Furthermore, they concluded that the sediment transport caused by saturation overland flow is more important for channel initiation in low-gradient conditions, whereas the role of shallow landslides is effective for channel initiation in steep conditions.

The studies by Montgomery and Dietrich (1988, 1989) and Dietrich *et al*. (1992, 1993) made progress in the channel initiation models, which explained the critical area-slope condition (this condition is denoted hereafter as ‘topographic threshold’) with physical properties of slope or channel material. In order to explain rainfall and topographic conditions for channel initiation simultaneously, however, these models require some problems to be improved. For example, they assumed a constant rate of rainfall condition.

The concepts of channel initiation suggested by Montgomery and Dietrich (1988, 1989) and Dietrich *et al*. (1992, 1993) were adopted in the simulation models for landform evolution as ‘channel initiation function’ (Willgoose *et al*., 1991; Tucker and Bras, 1998). Tucker and Bras (1998) introduced various channel initiation functions into the landform evolution models, and simulated the variation of area-slope relation and slope form by various hydro-geomorphic processes. However, the discussions in these studies are primary confined in simulated landscapes.

Recently, Istanbulluoglu *et al*. (2002) also analyzed the statistical distribution of thresholds for channel initiation in a granitic hill in Idaho. They recognized the distributions of several factors such as the grain size of sediment and surface roughness should affect the spatial variation of thresholds for channel initiation. The spatial variety of surface roughness or critical shear stress should complicate the calculation of conditions for channel initiation.

I-3: Thresholds for channel initiation based on observations

Hydraulic condition or topographic threshold for channel initiation was directly observed in the field. Many studies were carried out in the arid or semi-arid region where Hortonian overland flow occurs. For example, field observations in badlands and laboratory experiments revealed the hydraulic condition of rill flow and critical shear stress for rill initiation (Crouch and Novruzi, 1989; Slattery and Bryan, 1992; Merz and Bryan, 1993). Prosser and Dietrich (1995) and Prosser *et al*. (1995) observed hydraulic condition and critical shear stress for saturation overland flow through rainfall simulation in a grass land. They conducted experiments with various surface conditions and various discharge, and indicated that the critical shear stress on the grass land was five times larger than that on the clipped surface. They also discussed the relationship between observation and predicted thresholds for channel initiation. Recently, area-slope thresholds for gully initiation were evaluated in many field measurements (Vandaele *et al*., 1996; Vandekerckhove *et al*., 2000; Nachtergaele *et al*., 2001). Moreover, observed thresholds for gully initiation were compared with modelled thresholds (Prosser and Abernethy, 1996; Kirkby *et al*., 2003).

On the other hand, many studies on humid forested mountains focused on the analysis of the conditions for shallow landsliding based on DTMs (digital terrain models) (Montgomery and Dietrich, 1994a; Wu and Sidle, 1995; Montgomery *et al*., 1998). Few studies, however, directly measured area-slope thresholds for channel initiation in humid forested mountains after the work by Montgomery and Dietrich (1994b). Furthermore, few studies observed critical discharge for bedload transport in channel heads. More detailed observations would be required for the better understanding of channel initiation mechanism in humid forested mountains.

I-4: Objective and approach

The review of the previous studies suggests the lacks of (1) quantitative models for landform evolution based on the observed rainfall-runoff response and (2) field measurement of thresholds for channel initiation in humid forested mountains. There is a gap between hydro-geomorphic observations and channel initiation models in humid forested mountains. Thus, the estimation of thresholds for channel initiation is required based on hydro-geomorphic observations.

As described in the former section, many studies have treated channel initiation affected by shallow landslides. Although shallow landslides are one of the most dominant processes for landform evolution in humid forested mountains, shallow landslides do not always affect location of channel heads, which are identified with 'concentrated water flow and sediment transport between banks' (Dietrich and Dunne, 1993). The location of channel head is controlled by climatic change or recurrence interval of shallow landslides (Dietrich *et al.* 1987). Since the reported recurrence intervals of shallow landslides are over 100 or 1000 years (Reneau *et al*., 1986; Shimokawa *et al*., 1989; Yoshinaga and Saijo, 1989), shallow landslides affect channel initiation in the longer time scale (> 100 years). In the shorter time scale (< 100 y), however, bedload transport processes must strongly affect the channel heads. Moreover, shallow landslides are also controlled by bedrock lithologies. In Japan, for example, granitic mountain slopes have a number of shallow landslide scars (Iida and Okunishi, 1983; Onda, 1992), while only a few shallow landslides occur in mountains underlain by Mesozoic sedimentary rocks. Therefore, mountains underlain by Mesozoic sedimentary rocks have a smaller effect of shallow landslides on channel initiation than granitic mountains. As described later in the section III-2, a mountain underlain by Mesozoic chert in the eastern Ashio Mountains has only a few landslide scars. Bedload transport may be expected to distinctly affect channel initiation in the mountain. Thus, the objective of the present study is to analyze thresholds for channel initiation by bedload transport in a humid forested mountain underlain by Mesozoic chert in the eastern Ashio Mountains.

The present paper proposes a new method to estimate thresholds for channel initiation through coupling the concepts of process-based models with monitored field data on hydro-geomorphic processes (Figure 1). Rainfall-runoff condition is an item of the hydro-geomorphic observations at channel heads. The hydrological data observed at headwater basins and springs were used to quantify the relationship between discharge, source area and rainfall. Sediment transport is another item of observations. The critical discharge for bedload transport, which would be another important factor for channel initiation, was also evaluated with field observations. Finally, thresholds for channel initiation were estimated on the combination of rainfall-runoff relationship and critical discharge for bedload transport. Although long observation period must be required for discussion on realistic processes, the present paper discusses the channel initiation based on observations for three years (2000 – 2002).